Effect of Jordanian Steel Blast Furnace Slag on Asphalt Concrete Hot Mixes

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ABSTRACT

Significant quantities of slag are generated as waste materials or by-product from steel industries. They usually contain considerable quantities of metals. In this study, steel slag obtained from a steel factory in Jordan was used in Asphalt Concrete Hot Mixes (ACHM). Marshall specimens were prepared with 100% lime stone dense graded aggregates at 4.5, 5, 5.5 and 6% bitumen contents by weight of aggregate to serve as control specimens. Another set of Marshall specimens with 100% Steel Slag Aggregates (SSA) and another set with a combination of limestone and (SSA) were prepared using the same grading and bitumen contents. Test results showed a reduction in the Optimum Bitumen Content (OBC) and an increase in density and stability values for specimens prepared with 100% (SSA). A decrease in the flow, Percentage of air voids (P_{av}), and Voids in Mineral Aggregates (VMA) values - but in compliance with the recommended values by the Asphalt Institute- was observed in specimens prepared with 100% (SSA).

KEYWORDS: Slag, Air cooled steel slag, Asphalt mixes, Wearing course.

INTRODUCTION

Blast furnace slag is produced as a by-product during the manufacture of iron and steel. Significant quantities of steel slag are generated as the major by-product from the conversion of iron to steel in the basic steel making processes (Cement Australia Group). In Jordan, the estimated daily production of steel slag is 15 – 20 tons. The steel slag generated from the conversion of iron to steel is poured into beds and slowly cooled under ambient conditions. A crystalline structure is formed, and hard, lump slag is produced which can subsequently be crushed and screened (National Slag Association). The material produced by crushing and screening is the Steel Slag Aggregate (SSA).

Most of the produced steel slag in Jordan is utilized in the cement industry, and has never been used in asphalt hot mixtures or other fields of applications. This is due to the lack of information and research in these fields. Literature showed that the use of (SSA) in asphalt concrete hot mixes will result in an excellent product that meets the required specifications for the use in highways wearing courses (Emery).

In asphalt concrete hot mixes, the physical and mechanical properties of the used aggregates play the major role in determining the overall properties of the mixtures. It is found that the required physical and mechanical properties for asphalt concrete hot mixes are found in the (SSA) (Noureldin and McDaniel, 1990; George and John, 2004).

Steel Slag Origin

Steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and

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oxides that solidifies upon cooling. Virtually all steel is now made in integrated steel plants using a version of the basic oxygen process or in specialty steel plants (mini-mills) by using an electric arc furnace process. The open hearth furnace process is no longer used.

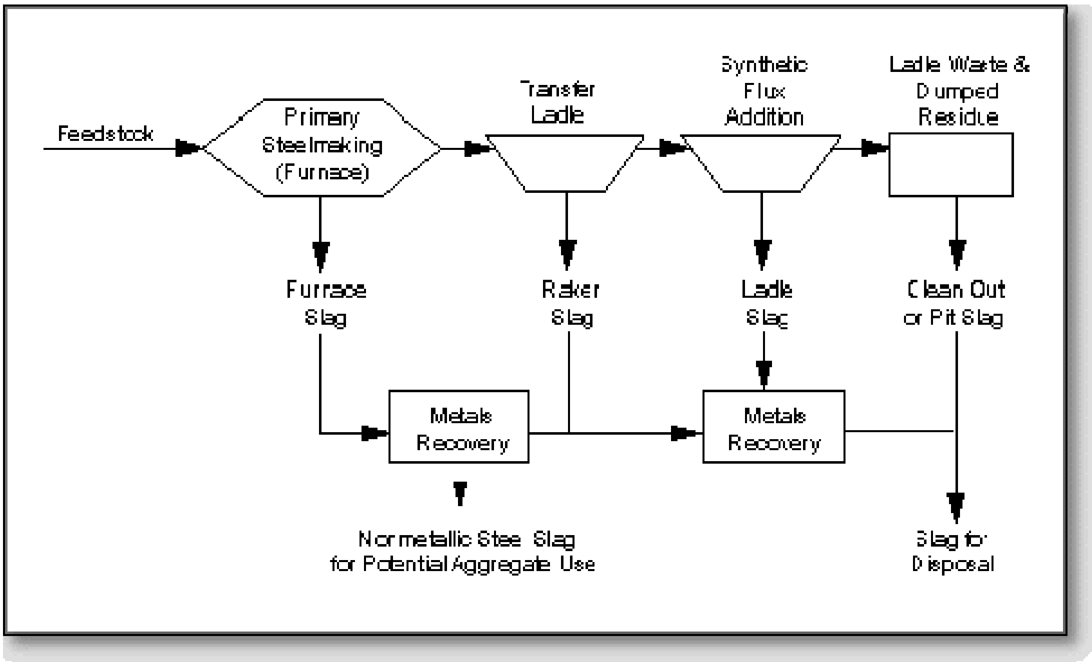
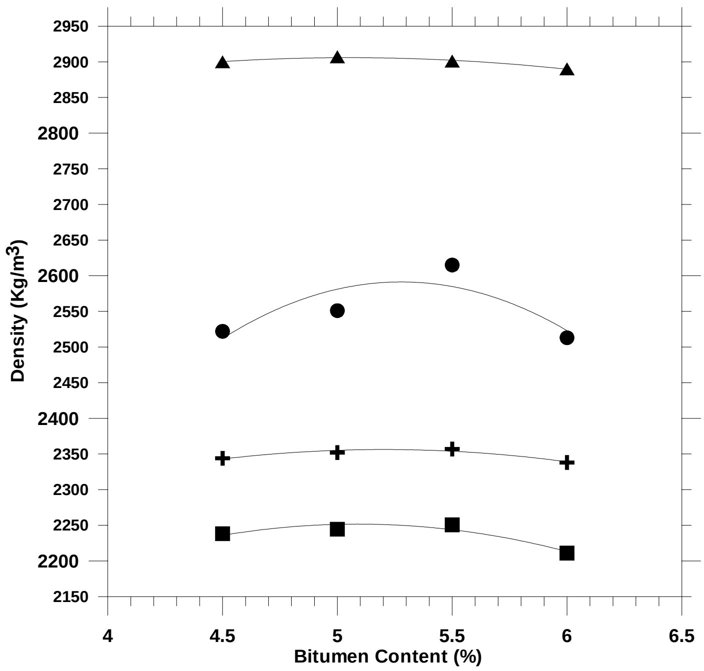


Figure (1): Overview of slag production in a modern integrated steel plant.



●	SSA) Coarse + Fine and Mineral Filler Limestone
▲	100% (SSA)
✚	Coarse and Fine Limestone + (SSA) Mineral Filler
■	100% Limestone

Note: Legend applies for Figures (2) to (6).

Figure (2): Density curves for different asphalt mixtures.

Table (1): Aggregate Combinations Used in Preparing Marshall Specimens.

Aggregate Combination	Bitumen Content (%)	Number of Specimens per each Bitumen Content
100% Limestone	4.5, 5, 5.5 and 6	4
100% (SSA)	4.5, 5, 5.5 and 6	4
Coarse (SSA) Aggregate +Fine and Mineral Filler Limestone Aggregates	4.5, 5, 5.5 and 6	4
Coarse and Fine Limestone Aggregates + Mineral Filler (SSA) Aggregate	4.5, 5, 5.5 and 6	4

In the basic oxygen process, hot liquid blast furnace metal, scrap and fluxes, which consist of lime (CaO) and dolomitic lime (CaO.MgO or "dolime"), are charged to a converter (furnace). A lance is lowered into the converter and high-pressure oxygen is injected. The oxygen combines with and removes the impurities in the charge. These impurities consist of carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolime to form the steel slag. At the end of the refining operation, the liquid steel is tapped (poured) into a ladle while the steel slag is retained in the vessel and subsequently tapped into a separate slag pot.

There are many grades of steel that can be produced, and the properties of the steel slag can change significantly with each grade. Grades of steel can be classified as high, medium and low, depending on the carbon content of the steel. High-grade steels have high carbon content. To reduce the amount of carbon in the steel, greater oxygen levels are required in the steel-making process. This also requires the addition of increased levels of lime and dolime (flux) for the removal of impurities from the steel and increased slag formation.

There are several different types of steel slag produced during the steel-making process. These different types are referred to as furnace or tap slag, raker slag, synthetic or ladle slags and pit or cleanout slag. Figure (1) presents a diagram of the general flow and production of different slags in a modern steel plant. The steel slag produced during the primary stage of steel production is referred to as furnace slag or tap slag. This is the major source of steel slag aggregate. After being tapped from the furnace, the molten steel is transferred in a ladle for further refining to remove additional impurities still contained within the steel. This operation is called ladle refining, because it is completed within the transfer ladle. During ladle refining, additional steel slags are generated by again adding fluxes to the ladle to melt. These slags are combined with any carryover of furnace slag and assist in absorbing deoxidation products (inclusions), heat insulation and protection of ladle refractories. The steel slags produced at this stage of steel making are generally referred to as raker and ladle slags. Pit slag and clean out slag are other types of slag commonly found in steel-making operations. They usually consist of the steel slag that falls on the floor of the plant at various stages of operation, or the slag that is removed from the ladle after tapping. Because the ladle refining stage usually involves comparatively high flux additions, the properties of these synthetic slags are quite different from those of the furnace slag and are generally unsuitable for processing as steel slag aggregates. These different slags must be segregated from furnace slag to avoid contamination of the slag aggregate produced. In addition to slag recovery, the liquid furnace slag and ladle slag are generally processed to recover the ferrous metals. This metal recovery operation (using magnetic separator on conveyor and/or crane electromagnet) is important to the steelmaker as the metals can then be reused within the steel plant as blast furnace feed material for the production of iron.

Management Options

Recycling

Hundreds of tons of steel slag are treated each year in the steel factories as a by-product for disposal until the quantity of slag in the slag storing yards has reached enormous amounts. The primary applications for steel slag as recycling materials are its use as a granular base or as an aggregate material in construction applications.

Disposal

While most of the furnace slag should be recycled for use as an aggregate, excess steel slag from other operations (raker, ladle, clean out or pit slag) is usually sent to landfills for disposal.

Highway Uses and Processing Requirements

Asphalt Concrete Aggregate, Granular Base and Embankment or Fill

The use of steel slag as an aggregate is considered a standard practice in many jurisdictions, with applications that include its use in granular base, embankments, engineered fill, highway shoulders and hot mix asphalt pavement.

Prior to its use as a construction aggregate material, steel slag must be crushed and screened to meet the specified gradation requirements for the particular application. The slag processor may also be required to satisfy moisture content criteria (e.g., limit the amount of moisture in the steel slag aggregate prior to shipment to a hot mix asphalt plant) and to adopt material handling (processing and stockpiling) practices similar to those used in the conventional aggregates industry to avoid potential segregation. In addition, as previously noted, expansion due to hydration reactions should be addressed prior to use.

THE NEEDS OF FACTORIES

With the increasing awareness of the need for sustainable development, the use of fresh (primary) aggregate in the concrete hot asphalt mixture layers of road or airfield pavement is seen as a wasteful use of a finite natural resource. Therefore, the recycling of primary aggregates and/or the use of waste (secondary) materials are recognized as being of benefit to both environment and society. Of the various waste streams, the by-products of the iron and steel making industries (steel slag and/or blast furnace) can be considered sensible alternative sources of aggregate for concrete and asphalt mixture productions and road bases. However, the potential classification by the U.S. Environmental Protection Agency (USEPA) of steel slag as hazardous wastes is of continuing concern to the steel industry.

The American Society of Testing and Materials (ASTM, 1999) defines the blast furnace slag as "the non-metallic product consisting essentially of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace". To the casual observer, one of the most striking features of an iron and steel plant is the site of mountainous slag pile that presents a continuous display as ladle after ladle pours its incandescent load down the side in the endless accumulation of this waste product. Moreover, these large amounts are deposited in slag storing yards, occupied farmland and silted rivers, polluting the environment for many years.

Resource recovery and reuse of waste materials have become very important within the past decade because of the increasing attention of the needs for environmental regulations in Jordan that force minimizing and / or safe waste disposal. This research focuses on studying the possibilities of recycling steel slag that is considered as a waste to be disposed by the factory in concrete mixtures and asphalt mixtures (as aggregates and sub-base materials). The work assesses the mechanical performance of concrete and asphalt mixtures using steel slag after incorporating different combinations, size fractions and percentages of steel slag and blast furnace with the primary aggregate (limestone).

Table (2): Grading for Limestone and (SSA) Aggregates Used in Marshall Specimens.

Aggregate Designation	Sieve Size (mm)	Retained (%)	Weight (gr.)
Coarse Aggregate	19.5	0	0
	12.5	20	220
	9.5	12	132
Fine Aggregate	4.75	23	253
	2.36	15	165
	0.425	21	231
	0.075	4	44
Mineral Filler	pan	5	55

Table (3): Specific Gravities and Absorption of Water by Limestone Aggregate.

Aggregate Size	Bulk Specific Gravity (G_{sb})	Absorption (%)
Coarse	2.60	3.2
Fine	2.50	5.1
Mineral Filler	2.75	N.A.

Table (4): Specific Gravities and Absorption of Water by (SSA) Aggregate.

Aggregate Size	Bulk Specific Gravity (G_{sb})	Absorption (%)
Coarse	3.26	1.7
Fine	3.22	2.5
Mineral Filler	3.7	N.A.

Table (5): Typical Mechanical Characteristics of Aggregates.

Aggregate Type	Aggregate Crushing Value, (%)	Los Angeles Abrasion, (ASTM C131), (%)	Sodium Sulfate Soundness Loss (ASTM C88), %	Angle of Internal Friction	California Bearing Ratio (CBR), % top size 19 mm
Limestone	30	29	12	49°	100
(SSA)	19	20.5	8	42°	>300

Table (6): Chemical composition of (SSA).

Component %	Percentage, %
Free Lime (CaO)	45.1
Silicon dioxide (SiO_2)	12.5
Iron (FeO or Fe_2O_3)	15.3 (75% FeO, 25% Fe_2O_3)
Manganese oxide (MnO)	4.8
Magnesium oxide (MgO)	8.9
Aluminum oxide (Al_2O_3)	4.1
P_2O_5	0.7
Titanium dioxide (TiO_2)	0.2
Sulfur (S)	< 0.1
Metallic Fe	8.3

The main objective of the steel factories is the production of steel deformed bars. A large amount of steel slag from the steel factory is treated as a by-product for disposal until the quantity of slag in the slag storing yards has reached enormous amounts. Environmental pollution, rising costs and decreasing capacity at landfills have forced the factory of steel industry to change this view. The effective utilization of blast furnace steel slag has become an important part in the steel market and must be taken seriously as a resource for recycling, concrete hot asphalt mixes and environmental protection. This research proposes innovative slag waste recycling technologies for steel plants with the ultimate objective of zero waste or 100% recycling.

RESEARCH PROCEDURE

For the evaluation of the effect of using SSA in asphalt mixes, Marshall specimens using limestone aggregate were prepared at 4.5, 5, 5.5 and 6 % by weight of aggregate to be compared with those prepared with 100% (SSA) aggregate and (SSA) mixed with limestone aggregate at the same bitumen content. Table (1) shows the aggregate combinations used in preparing Marshall specimens. The Optimum Bitumen Content (OBC) for specimens prepared with 100% limestone aggregate that is used in hot mixes for wearing course - in Jordan - is around 5.5% (MPWH, Jordan). All specimens were prepared in accordance to ASTM D3515 and ASTM D1559 standards in the form of dense graded particles with nominal maximum particle size of 12.5 mm (ASTM, 1998).

For the evaluation of physical and mechanical characteristics of both limestone and (SSA) aggregates, several tests were conducted, including specific gravity test according to ASTM D70 standards, crushing value test according to BS812-Part 110 standards, Los Angeles abrasion value test according to ASTM C131-76 standards and absorption test according to ASTM C127-77 standards. Consistency tests on asphalt, including tests of penetration, specific gravity, softening point and ductility were also conducted.

MATERIALS USED

Bitumen

The bitumen used in preparing all specimens was with a penetration value of 60-70 (tenth of mm), specific gravity of 0.97, softening point of 51^{o}C and ductility of 100+(cm).

Limestone and Steel Slag Aggregates

Grading

Grading of aggregates used in preparing Marshall's specimens sets are shown in Table (2). The grading consisted of coarse aggregate (retained on sieve No. 4), fine aggregate (passing sieve No. 4 and retained on sieve No. 200), and mineral filler (passing sieve No. 200). This grading represents an improvement in the grading of the mixture, and it lies closer to the Fuller maximum density curve. From basic soils' principles, this alone will give the mixture better mechanical properties than the individual slags alone.

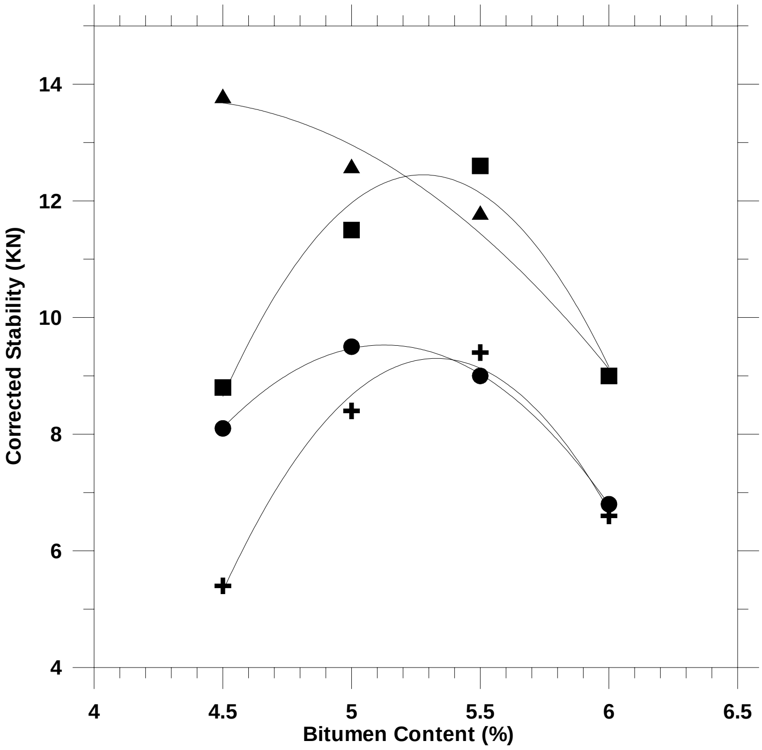


Figure (3): Corrected stability curves for different asphalt mixtures.

Physical Properties

Steel slag aggregates are highly angular in shape and have a rough surface texture. They have high bulk specific gravity and moderate water absorption (less than 3 percent). Tables 3 and 4 list some typical physical properties of limestone and Steel Slag Aggregates (SSA).

Mechanical Properties

It is noted that processed steel slag has favourable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics and high bearing strength. Table (5) lists some typical mechanical properties of steel slag.

Chemical Properties

The chemical composition of slag is usually expressed in terms of simple oxides calculated from elemental analysis determined by x-ray fluorescence. Table (6) lists the range of compounds present in steel slag from a typical base oxygen furnace. Of more importance is the mineralogical form of the slag, which is highly dependent on the rate of slag cooling in the steel-making process. The cooling rate of steel slag is sufficiently low so that crystalline compounds are generally formed. The predominant compounds are dicalcium silicate, tricalcium silicate, dicalcium ferrite, merwinite, calcium aluminate, calcium-magnesium iron oxide and some free lime and free magnesia (periclase). The relative proportions of these compounds depend on the steel-making practice and the steel slag cooling rate.

Free calcium and magnesium oxides are not completely consumed in the steel slag, and there is general agreement in the technical literature that the hydration of unslaked lime and magnesia in contact with moisture is largely responsible for the expansive nature of most steel slags. The free lime hydrates rapidly and can cause large volume changes over a relatively short period of time (weeks), while magnesia hydrates much more slowly and contributes to long-term expansion that may take years to develop.

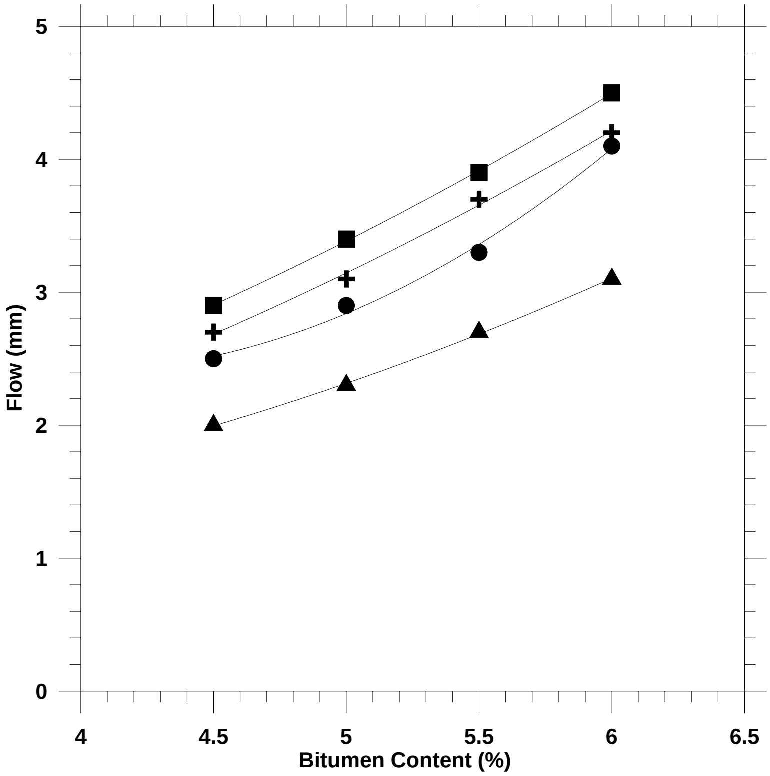


Figure (4): Flow curves for different asphalt mixtures.

Steel slag is mildly alkaline, with a solution pH generally in the range of 8 to 10. However, the pH of leachate from steel slag can exceed 11, a level that can be corrosive to aluminum or galvanized steel pipes placed in direct contact with the slag. The free lime in steel slags can combine with water to produce calcium hydroxide [$Ca(OH)_2$] solution. Upon exposure to atmospheric carbon dioxide, calcite ($CaCO_3$) is precipitated in the form of surficial tufa and powdery sediment in surface water. Tufa precipitates have been reported to block drainage paths in pavement systems.

Thermal Properties

Due to their high heat capacity, steel slag aggregates have been observed to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous in hot mix asphalt repair work in cold weather.

PREPARATION OF MARSHALL SPECIMENS

Marshall specimens were prepared and tested according to ASTM D1559 (Cement Australia Group). For all specimens, aggregate and bitumen were heated at temperatures of 140 and 180 ^oC, respectively. Specimens were compacted with 75 blows of Marshall's hammer on each side to count for heavy traffic category. Specimens were extracted from the molds and kept at ambient temperature for one day. Necessary data for obtaining the specific gravity, Percentage of air voids (P_{av}), Voids in Mineral Aggregates (VMA) and to count for stability correction were measured and recorded. These data are mainly the weight in air and water and the height of the specimens. To conduct the Marshall stability and flow tests, the specimens were kept in a water bath at 60°C for 30 minutes. The (OBC) for specimens prepared with different aggregate combinations was determined according to Marshall stability, specific gravity, percentage of air voids and voids in mineral aggregate.

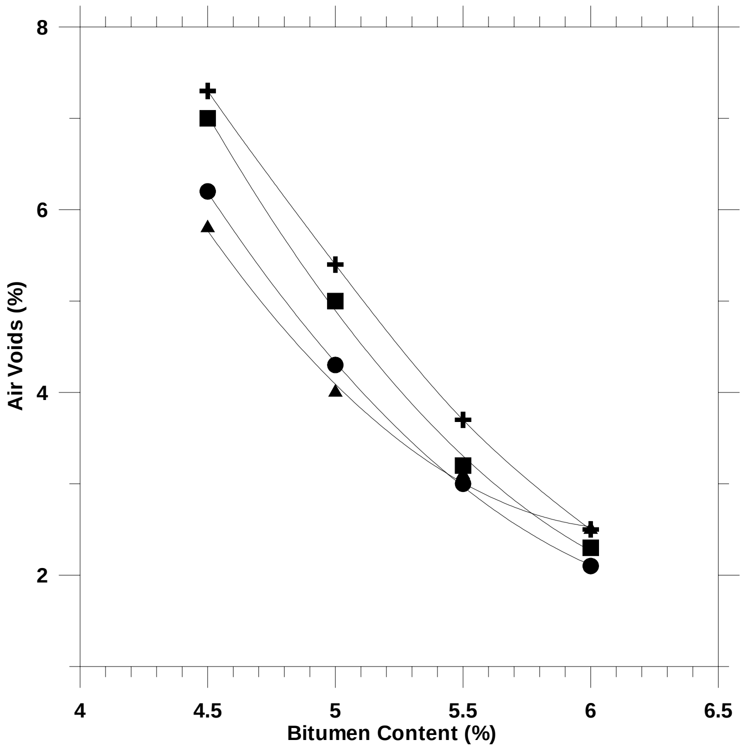


Figure (5): Air voids curves for different asphalt mixtures.

ANALYSIS OF MARSHALL TEST RESULTS

The Marshall test results on the prepared specimens showed that the OBC was reduced from a value of 5.3% in the case of specimens prepared with 100 % limestone (control specimens) to a value of 4.8% for specimens prepared with 100 % (SSA). The reason is due to the low absorption value of the (SSA) used. The OBC values for specimens prepared with combined aggregates ranged between 5%, 5.2% and 5.4% for specimens prepared with coarse and fine (SSA)+limestone mineral filler, with coarse (SSA)+fine and mineral filler limestone aggregates and with coarse and fine limestone aggregates+(SSA) as mineral filler, respectively.

When density and stability values are considered, specimens prepared with 100 % (SSA) had the highest density and stability compared with the control specimens and specimens prepared with a combination of (SSA) and limestone aggregates, as shown in Figures (2) and (3), respectively. It is believed that the reason for this is due to the low crushing and Los Angeles abrasion values of the (SSA) when compared to limestone aggregates as indicated in Table (5).

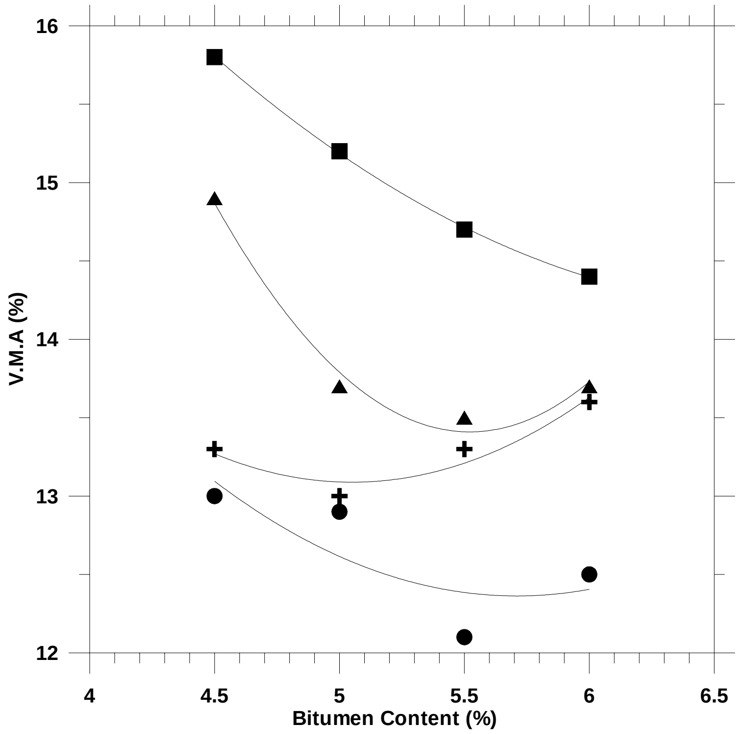


Figure (6): V.M.A. curves for different asphalt mixtures.

A slight decrease in the flow value was noticed in the case of specimens prepared with 100% (SSA) when compared to the control specimens. The curves shown in Figure (4) show that all specimens prepared at their (OBC) are in the range recommended by the Asphalt Institute (between 3-5 mm for the surfacing and heavy traffic category) (The Asphalt Institute, Lexington, 1993). The Percentage of air voids (P_{av}) and VMA for specimens prepared with 100% (SSA) decreased when compared to the values of the control specimens as shown in Figures (5) and (6), respectively. The particle shape, grading and maximum nominal size for the aggregate used play the major role in the determination of these values. It is important to mention that the P_{av} and VMA values obtained for specimens prepared with 100% (SSA) and the control specimens comply with the values recommended by the Asphalt Institute (minimum of 4% P_{av} value for heavy traffic, and 12.5% minimum VMA value for specimens prepared with gradation of maximum nominal size of 12.5 mm) (The Asphalt Institute, Lexington, 1993).

CONCLUSIONS

Research results showed that Steel Slag Aggregates (SSA) have particle properties that can improve the performance of asphalt concrete hot mixes. It is also noticed that the optimum bitumen content (OBC) value could be reduced with the use of (SSA) in asphalt concrete hot mixes (ACHM). Finally, ACHM made with SSA can be used successfully in highways wearing course where the high stability and consequent rutting resistance is an important asset. Thus, it is recommended that the producers and the users of (ACHM) in Jordan consider the use of (SSA). Further research is still required to obtain new specifications for the use of (SSA) in different fields of application to conserve Jordan natural resources. Given the high strength of the materials and the potential employment creation benefits, the research on these materials is continuing.

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